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Estimates of Performance and Cost for Boost Phase Intercept

By Gregory Canavan

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With

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Dr. Gregory Canavan has worked in the area of missile and defense technologies for over twenty-five years. He has served as Director of the Office of Inertial Fusion at the Department of Energy and as Deputy to the Air Force Chief of Staff. Since 1981, Dr. Canavan has been Scientific Advisor, Physics Division of Los Alamos National Laboratory. In 2000, he was elected a Fellow of the American Physical Society for his contributions in military science and technology and their transfer to the civilian sector. He is a member of the Marshall Institute Board of Directors.

Estimates of Performance and Cost for Boost Phase Intercept*

Dr. Gregory Canavan
September 24, 2004

Jeff Kueter: It is my pleasure to welcome you all here this afternoon for another in our continuing series in the Washington Roundtable on Science and Public Policy. The Washington Roundtable is a speaker series designed to bring scientists and engineers to Washington to talk to the policy community issues. With the recent interest in boost-phase missile defense, we thought it particularly important to ask Dr. Gregory Canavan to come in and talk through some of the analyses that are making their way through Congress and the defense community. Dr. Canavan's emphasis is on space-based defense and the importance that changing different assumptions make in the final end analyses.

Dr. Canavan, of course, is a long-time associate of the Marshall Institute and a member of our Board of Directors. An active participant in the area of missile defense technologies for over twenty-five years, he has served as Director of the Office of Inertial Fusion at the Department of Energy and as Deputy to the Air Force Chief of Staff. Since 1981, he has been Scientific Advisor, Physics Division of Los Alamos National Laboratory. In 2000, he was elected a Fellow of the American Physical Society for his contributions in military science and technology and their transfer to the civilian sector. Please join me in welcoming Dr. Gregory Canavan.

Dr. Canavan: Thank you very much. It is an honor to be invited back. The occasion for this talk was that Dr. Jastrow had read a couple of these reports and asked me some questions about performance and cost of various boost phase systems. By the time I got through answering all of his questions, I found that I had written a short note and he then asked me to give a talk on it because other people might be interested in looking through some of the insights that I had generated in the process. So that is what I will do here.

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* The views expressed by the author are solely those of the author and may not represent those of any institution with which he is affiliated.

I. Introduction

This note discusses the performance and cost of missile defense by space-based interceptors (SBI) in the boost phase. It is stimulated in part by the American Physical Society (APS) Report "Boost-Phase Intercept Systems for National Missile Defense,"[1] which estimates SBI and constellation masses, and the Congressional Budget Office (CBO) Report "Alternatives for Boost-Phase Missile Defense," which estimates constellation and life cycle costs.[2] This report compares the mass and cost estimates of those reports to those of the analytic models derived here.

To summarize briefly, this note's predictions of SBI range, mass, and constellation sizes agree to within a few percent with those of the APS Report for the conditions of that report, which disagree by 25 to 50% with the CBO Report. For coverage of liquid fueled missiles by uniform constellations by space based interceptors (SBI) with light Kill Vehicles (KV), all three reports derive optimal SBI speeds ≈ 4 km/s, constellations ≈ 220 SBI, and mass on orbit ≈ 50 tonnes.

The APS Report does not treat costs other than those of launch. The CBO provides a survey of historical military space system costs. This report provides a complementary data base for high volume production of small SBI based on the recent IRIDIUM system and a framework for comparing those data sets and the limited detailed costing the Department of Defense (DoD) has done on space based systems in this mass class.

For CBO data base costs, KV costs dominate SBI cost. For the IRIDIUM database, launch and booster costs dominate. IRIDIUM costs optimize mass on orbit at cost ≈ \$2.5B and SBI speed ≈ 4 km/s. As costs increase to CBO levels, the total costs only increase to ≈ \$4B and SBI speed to ≈ 5 km/s. With CBO estimates of fixed cost, that produces life cycle costs of ≈ \$20B for defense against liquid missiles and \$48B for solids, which are comparable to those for other strategic systems and to other elements of the current missile defense system.

Kinematic and component cost issues are important, but total system costs are more sensitive to the SBI constellation. The APS and CBO

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[1] Boost-Phase Intercept Systems for National Missile Defense (Report of the American Physical Society, July 2003).
[2] Alternatives for Boost-Phase Missile Defense (U.S. Congress, Congressional Budget Office, July 2004).

Reports assume that it is necessary to cover all latitudes uniformly, based on the assumption on that rogue countries will quickly develop mobile ICBMs. Rogue missiles are more likely to launch from fixed sites, in which case inclining constellations over the threat latitude can increase coverage there an order of magnitude. This concentrated coverage reduces the number of SBI needed for coverage and decreases the interval between successive SBI. It is the optimal way to deploy additional SBI as they become available as well as to achieve whatever end state is ultimately necessary.

Concentrated coverage reduces the number of SBI for initial coverage by a factor of 2 to 5 and the mass on orbit by like amounts. The APS Report's main concern with SBI was that uniform coverage of fast burn solid missiles might take ≈ 2,000 tonnes, which could stress U.S. lift capacity. Concentrated coverage with would only take ≈ 30 tonnes for liquid missiles, which is two orders of magnitude lower and could be accommodated on a single launcher. Concentration also reduces optimal speeds to ≈ 2 km/s, which simplifies SBI and engine components.

These reductions in mass on orbit imply similar reductions in cost. While uniform coverage of solid missiles could cost ≈ $12B, concentrated coverage of liquid missiles would drop to ≈ $1.3B. The costs for replacement constellations and fixed costs are significant contributions to life cycle costs, but not excessive when appropriate estimates of R&D, integration, operations, and test costs are used.

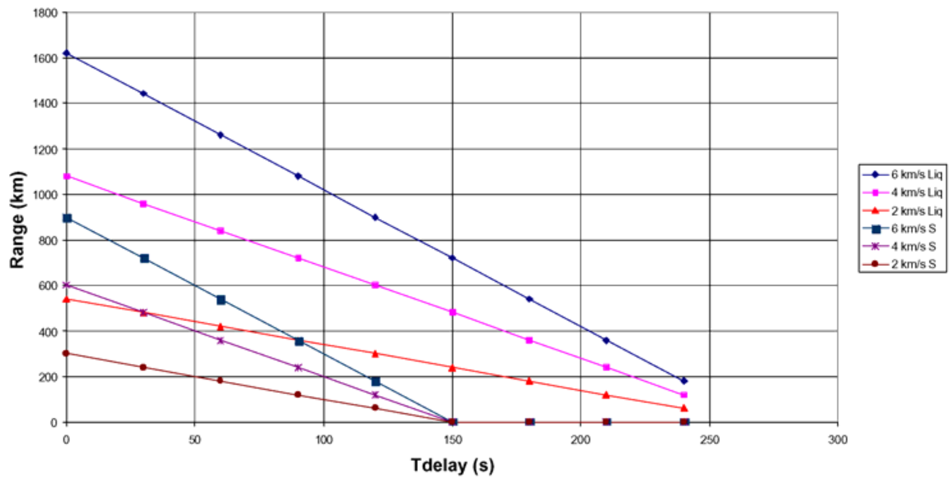
Concentration is the appropriate way to get coverage where it is needed as soon as possible with a limited number of SBI and the optimal path to the ultimate configuration. Global defenses can evolve with constellations slightly larger than those for concentrated coverage. Modest investment could protect the needed technology options and SBI timelines and provide assurance against the evolution countermeasures that surface-based systems cannot overcome.

Section II compares the reports' predictions of range, KV mass, and SBI mass. Section III discusses their approach to sizing uniform SBI constellations, and IV compares their resulting masses in orbit. Section V compares constellation and life cycle costs from the CBO Report and this note. Section VII derives the coverage from 3 constellations concentrated over limited threats; converts it into required constellations sizes, masses, and costs; and derives the order of magnitude reductions in mass and cost that produces for individual threats. Section VIII indicates how concentrated constellations merge into wider coverage as additional threats emerge. Sections IX and X summarize and conclude the discussion.

II. SBI Characteristics

The APS and CBO Reports and this note each use largely analytic models for SBI ranges and masses. Their models differ to varying extents. This section compares the models used in and results. Overall, the predictions of this note agree with those of the APS Report for those parameters to within a few percent. It only agrees with the range and mass predictions of the CBO Reports to within 25-50%. The reasons are explained. They do not overly complicate subsequent comparisons.

Fig. 1. SBI range vs Tdelay



Kinematics. This note uses an analytic model for SBI range R as a function of maximum speed, V, acceleration, A, and release delay time, T_D, to intercept missiles of burn time, T_M. The delay for SBI release T_D and the time accelerate to full speed V/A subtract from the SBI's total flight time, so it range is

$$R = V(T_M - T_D - V/2A), \qquad (1)$$

which is exact for SBI with constant acceleration. The resulting ranges shown in Figure 1, agree with the APS Report's to within about 5%. The difference is largely due to a slight reduction of range by non-uniform acceleration. For intercept of a liquid missile with a T_M = 5 minute burn time by a SBI with V = 4 km/s, A = 10g, and T_D = 60 s, Fig. 1 or Eq. (1) give R ≈ 840 km. That agrees with the value from the APS Report (p. 107, Fig. 6.2) to the accuracy to which it can be read. Alternatively, for a SBI with

T_D = 60 s and A = 7g intercepting a solid fuel missile with burn time T_M = 3 minutes, Fig. 1 gives R ≈ 360 km, which also agrees with Fig. 6.2 of the APS Report.

The CBO does not specify its method of calculating kinematic parameters, citing instead internal CBO reports for the predictions shown in its graph (p. 9, Fig. 2-2). There are discrepancies between the CBO's predictions and those of the APS and Eq. (1). For a liquid fueled missile with T_M = 5 min, CBO Fig. 2-2 it indicates that a SBI with V = 6 km/s, T_D = 0, and A = 6 km/s / 60 s = 10g has range ≈ 1,000 km. For those conditions the APS Fig. 6.2 gives R ≈ 1,200 km and Eq. (1) gives R = 6 km/s (300 s – 60 s - 30 s) = 1,260 km. Thus, the APS and this note are within about 5%, but their prediction disagrees with the CBO's by a 5-fold larger amount.

This 1,260/1,000 ≈ 1.26-fold discrepancy between the range prediction of the CBO and the APS and this note produces a $\approx (1.26)^2 \approx 1.5$-fold discrepancy in CBO constellation sizes. As it is straightforward to trace the impact of these discrepancies on constellation sizes and masses, it is not a major impediment to comparisons below.

Kill Vehicle masses. The CBO does not estimate KV masses; instead, it uses the 136 and 30 kg KVs discussed in the APS report (p. 126) for its studies. KV mass is the key element of any comparison, as the total mass on orbit is a simple multiple of it. The CBO (xviii) and APS describe the 30 kg KV as requiring more development than the 136 kg KV, but the main difference between the two is a matter of integration. Both KVs assume the set of sensors used by Clementine in re-mapping the moon. The APS's 136 kg KV assumes they would be flown with separate optical benches, as in Clementine. Doing so saved schedule time, but produced a 7 kg sensor package, much of which was the weight of the multiple optical benches. To that the APS added 9 kg of avionics and 1 kg of shielding, which were not found necessary on previous or subsequent designs; 4 kg of structural mass; and 2 kg of power for a total payload of 22.6 kg. The remaining 136 – 22.6 = 113.4 kg is the engine and fuel to provide 2.5 km/s divert.

CBO's Appendix B discussion of the integration of Clementine sensors on a common optical bench produces a ≈ 2.5 kg sensor package. It omits the unnecessary shielding, reduces avionics to 0.8 kg and structure to 0.5 kg using integral fuel tanks, which produces a ≈ 5.7 kg payload. The engine required for a payload of that size weighs ≈ 5.5 kg amount for a dry KV weight of ≈ 11.2 kg. With 19 kg of fuel, that KV could produce 2.5 km/s divert using engine technology that has been tested in flight. There is no fundamental technical difference between the two KVs in terms of risk; the main difference is in the levels of integration needed to put existing sensors into a common package for the 30 kg KV. The rate at which that integration can be accomplished is primarily limited by the rate of R&D on that area. At present little is spent on the pacing issue. Either KV could be available on the time scales discussed by the APS and CBO. Thus, this note uses the light and heavy KVs as appropriate for comparisons.

KV engines amount to ≈ 83% of the APS and CBO 30 kg KVs. Historically, it has been difficult to produce efficient small engines in this weight class, so significant weight penalties are assumed for the ≈ 2.5 km/s divert velocities postulated.[3] The KV payload, P, fuel, X, and thrust, W, have mass penalties associated with them estimated by the APS Report (p. 121) to be p = 0.05, x = 0.087, and w = 0.0009 kg/N. Fuel tanks add mass yX, where y ≈ 0.1-0.2. The product of the fuel expended and its specific impulse, $I_{SP} = c/g$, divided by the burn time of the stage, T_S , gives its approximate thrust $W = Xc/T_S$, so the KV inert mass is

$$M_I = pP + xX + yX + wW = pP + (x + y + wc/T_S)X = pP + zX, \qquad (2)$$

where $z = x + y + wc/T_S$. The total KV payload, fuel, and inert mass is

$$M_S = P + X + M_I = (1 + p)P + (1 + z)X = p'P + z'X. \qquad (3)$$

The engine is assumed to add velocity V_S. Its initial weight is M_S, and its final mass is $M_S - X = p'P + zX$, for which the ideal rocket equation gives

$$ES = \exp(V_S/c) = M_S/(M_S - X) = (p'P + z'X)/(p'P + zX), \qquad (4)$$

which can be solved for $X/P = (E_S - 1)p'/[1 - z(E_S - 1)]$, from which the stage mass is

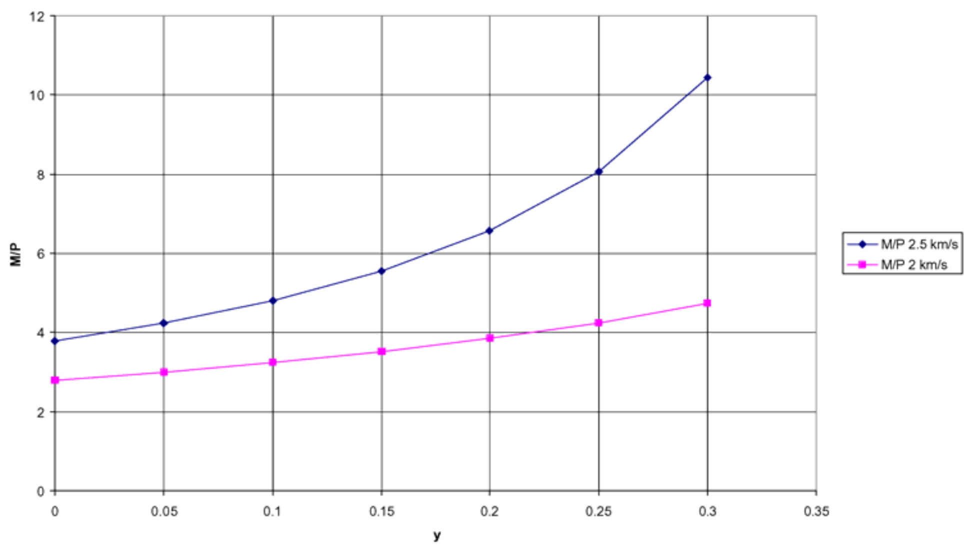
$$M_S = p'P + z'X = \{1 + (E_S - 1)/[1 - z(E_S - 1)]\}p'P = E_S/[1 - z(E_S - 1)]p'P, \qquad (5)$$

Figure 2 shows M_S/P as a function of the tankage penalty y. At 2 km/s divert, M/P increases from ≈ 3.2 at the y ≈ 0.1 of advanced tanks to 3.8 by the y ≈ 0.2 of conventional pressure-fed systems in this mass range, which

[3] G. Canavan, "SBI Stage Models," Los Alamos Report LA-UR-03-6032.

is an increase of ≈•20%. For 2.5 km/s divert M/P increases from ≈ 4.8 at y = 0.1 to 6.6 at y = 0.2, an increase of ≈ 38%. Those increases agree closely with the APS KV 136/22.6 ≈ 6 above. The mass ratio for y = 0.2 KV at 2.5 km/s is ≈ 6.6/3.2 ≈ 2.0-fold greater than that for a y = 0.1 KV with 2 km/s divert, which shows the importance of efficient engine tankage and divert design.

Fig. 2. M/P vs tankage penalty y for Vs = 2 & 2.5 km/s



Viewed another way, KVs typically have tankage penalties y ≈ 0.2, so they are strongly sensitive to the divert velocity desired. SBIs typically have tankage penalties y ≈ 0.1, so they are much less sensitive to the axial and any divert velocity desired.

One issue that is not tested below is the sensitivity of KV mass to end game acceleration. The APS assumes the KV lunge at 15g in the final stage of pursuit, but its analysis does not fully incorporate the mass penalties involved. The analysis above has been extended to treat final stage acceleration in a self-consistent manner.[4] At 2 km/s a 15g final acceleration increases M/P by 25%. At 2.5 km/s 15g increases it by ≈ 40%, again indicating the importance of careful determination of divert required. As the other reports do not treat end game acceleration, this report does not pursue it further.

[4] G. Canavan, "Impact of End-Game Acceleration on KV mass," Los Alamos Report LA-UR-03-6192.

SBI mass is related to KV masses through models of booster performance similar to those for KVs. The APS and CBO do not specify their booster models. This note uses an analytic model in which a booster is characterized by the four parameters used above: x, y, w, and c. For ≥ 30 kg KVs, SBI engines weigh several hundred kilograms. Thus, they are more efficient, tankage penalties are reduced, mass penalties of $x \approx y \approx 0.5$ are more appropriate, and the stage to payload mass reduces to

$$M_{SBI}/KV = [(1 + p)E/[1 - z(E - 1)]^n. \qquad (6)$$

Where n is the number of stages and E = V/nc. The APS and CBO reports generally use n = 2 stage interceptors, which are used for comparison below.

Fig. 3. Space-Based Interceptor SBI mass vs speed V
option 4 KV SBI = 140 kg; opt 5 = 30 kg

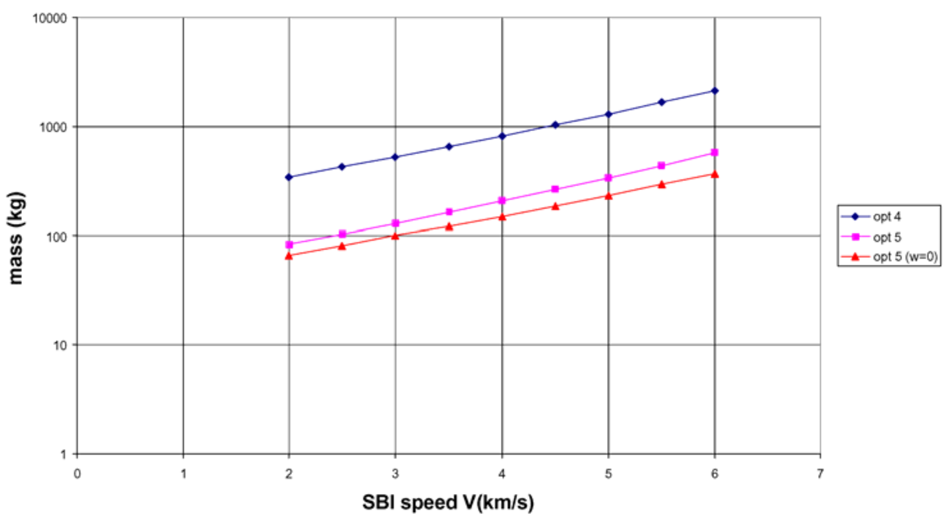


Figure 3 shows Eq. (6)'s predictions of SBI booster performance. The results labeled CBO options 4 and 5 have KV masses of 134 and 30 kg and design velocities of 4 and 6 km/s, respectively. The top curve for option 4 gives a SBI mass of 820 kg, which is within 3% of the 847 kg in the CBO Summary Table 2, and identical to the APS value of 820 kg (p. 126, Table 6.6). Because they use common booster scaling and design parameters, agreement for option 4 actually implies agreement between the APS and the predictions of this note at all masses and velocities of interest.

The middle curve is for comparison with CBO option 5. At its 6 km/s design speed the middle curve gives a mass of 576 kg, which is 30% higher than CBO's 442 kg (p. xvii, Table 2). The explanation is the CBO's different treatments of thrust penalties,[5] the weight that must be added to a SBI's to strengthen it withstand large accelerations. The APS surveyed a range of boosters and deduced a value of w = 0.9 kg/N (p. 121, Eq. 6.7), which is also used in this note, that enters the mass ratio of Eq. (6) in a complex, nonlinear way. The CBO uses a fixed penalty of 10%.

Turning the thrust penalty off altogether produces the bottom curve on Fig. 3. While the bottom two curves appear close in a logarithmic presentation, the bottom two curves are a significant distance apart. At CBO option 5's 6 km/s design speed the bottom curve gives 372 kg, which is 15% below the CBO value. As the CBO agrees closely with the APS and this model at low V, where the penalty is small, and disagrees with them at large V, where it is significant, it appears that the CBO's constant percentage treatment of the thrust penalty accounts for the difference in SBI masses.

For the comparisons below, it suffices to note that CBO SBI masses agree closely with the APS estimates and those of this note for CBO 4 km/s option 4 and are ≈ 30% lower than the APS and this note for its 6 km/s option 5. APS and this note's estimates below use the conventional thrust penalty, hence they are conservative, producing total masses on orbit ≈ 30% that are larger than the CBO's. As the discussion below indicates that the speeds of ≈ 4 km/s are of greatest interest, the differences at 6 km/s would appear to be of lesser concern.

SBI Lifejackets are exterior appendages that contain certain power, propulsion, station keeping, communication, etc. components needed to support SBI life in the dormant stage before release but not necessary for their later operation. When the SBI is activated to pursue a missile in boost, speed is at a premium. Equation (6) shows that speed depends strongly on the ratio of the initial to final mass of the SBI, which is maximized by jettisoning components that are not needed for intercept. In early SBI development it was estimated that the lifejacket might weight about 50% as much as the wet SBI. That fraction has tended to persist and gain credibility over time, although it has never been supported by a specific lifejacket design.

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[5] G. Canavan, "Impact of Thrust-Mass Coupling on Kill Vehicle Mass Estimates, Los Alamos Report LAUR-04-0696.

The APS report lists elements that might be appropriate for inclusion in the lifejacket, and suggests that their weight might total 50% of the SBI's, although it does not provide detailed component mass estimates. The CBO report suggests the lifejacket weight might be on the order of 50% for option 4 and drop to 20% for its later option 5, although again no detailed component masses are estimated. This note uses those values as ranges for comparisons, although there currently is no detailed specification of lifejacket components or masses. This uncertainty is less important at the lower optimal SBI velocities discussed below, for which the distinction between SBI and lifejacket mass is less critical as the penalty for the latter is only a factor of ≈ 5 according to Fig. 2.

Summary. All three reports use largely analytic models for SBI ranges and masses. This note's models appear to be more than adequate for any comparison of interest. Their predictions agree closely with those of the APS Report for SBI range and mass parameters to within a few percent. They disagree to ≈ 25% in range with the CBO Report, for which no basis is given, and ≈ 50% in mass, for reasons that can be traced to the CBO's treatment of SBI thrust penalties. The APS and CBO Reports do not study KV composition or mass explicitly. The APS and this note agree closely on KV and SBI engine performance. Thus, they agree closely on SBI mass given sensor package mass. There is agreement on lifejacket fraction, although that is not supported by a detailed understanding of lifejacket composition or scaling with SBI speed. These disagreements are significant but do not significantly impact the comparisons below.

III. Constellation Sizing

This section presents the analysis of constellation coverage and determines the constellation sizes required to support the uniform coverage assumed by the APS and CBO Reports.

Coverage. An SBI with flyout range R can cover missiles from an area ≈ πR2, and the surface area of the Earth is 4πRe 2, so it would take N ≈ 4πRe 2/πR2 = (2Re/R)2 SBI to approximately tile the surface of the Earth uniformly. However, it is not necessary to cover the whole Earth, as some latitudes currently contain no threats. To produce a uniform distribution of satellites between latitudes θ_1 to θ_2 requires a distribution over SBI inclination, i, of[6]

[6] G. Canavan, "Concentration of Space Based Interceptor Constellations," Los Alamos Report LA-UR-02-5739.

$$df = di \sin i \cos i / \sqrt{(\cos^2 i - \cos^2\theta_2)}, \quad (7)$$

which integrates to give

$$f(\theta_1, \theta_2) = \int_{\theta_1}^{\theta_2} dN = \sqrt{(\cos^2\theta_1 - \cos^2\theta_2)}, \quad (8)$$

as the fraction of the full constellation N needed to uniformly cover the area between latitudes θ_1 and θ_2. For $\theta_1 = 0$ and $\theta_2 = \pi/2$, this is $\sqrt{(\cos^2 0 - \cos^2\pi/2)} = \sqrt{(1 - 0)} = 1$, so global, uniform coverage would require $f(2R_E/R)^2 = (2R_E/R)^2$ satellites, as expected.

Fig. 4. Fraction of full constellation needed for uniform coverage vs lower latitude

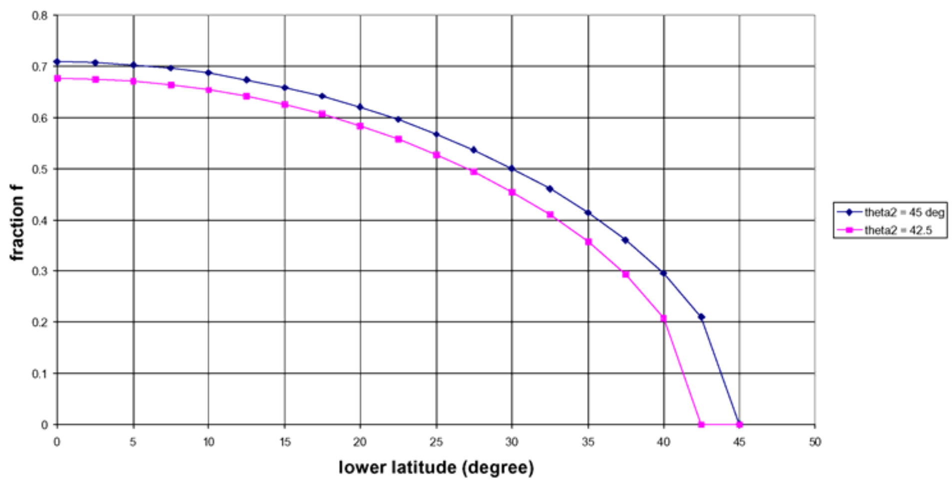


Figure 4 shows f as a function of the lower latitude of coverage θ_1 for upper latitudes of θ_2 = 42.5 and 45 degrees. The top curve for θ_2 = 45 degrees falls from f = 0.71 for θ_1 = 0, i.e., uniform coverage from the equator to 45 degrees, to 0.57 for coverage from θ_1 = 25 degrees to 45 degrees. The CBO uses the band 25 to 45 degrees for North Korea and Iran. North Korea only extends to $\theta_2 \approx 42.5$, which is represented by the bottom line. It has value f = 0.53 at θ_1 = 25. That reduces the CBO constellation by ≈ 7%, which indicates the rough accuracy of geometric coverage estimates.

The CBO suggests the extension of North Korea to 45 degrees is necessary to account for northerly launches from North Korea, but if such a correction is made, it would be appropriate to increase Iran's lower latitude by the same amount, which would cancel the correction from North Korea, leaving a net correction of zero. As this coverage correction is multiplicative and reduces all constellation sizes and masses by the same ≈ 7%, the 25-45 degree CBO band is used below to simplify comparisons.

Constellation sizes. The CBO and APS reports assume 2 SBI are launched at each missile from a uniform constellations, which together with Eq. (8) gives

$$N = 2f(2R_E/R)^2, \tag{9}$$

whose predictions are within 10% of the APS for the conditions of that report (APS, p. 118, Table 6.4). The CBO report provides SBI constellation size and mass for double coverage of a liquid missile by options 4 and 5 SBI, which are shown in columns two and three of Table I (p. xvii, below Table 2). For option 4 the CBO gives 386 SBI. The faster option 5 drops to 156. Their total masses on orbit are 468 and 83 tonnes, respectively. The bottom row gives the ratio of SBI mass to number. For option 4 that is 1,272 kg, which is equal to the CBO's 847 kg KV mass, multiplied by its assumed life jacket penalty of 1.5. Option 5's 532 tonne mass is equal to the 442 kg SBI mass times its smaller life jacket of 1.2.

Table I. Constellation size and mass for liquid missiles for uniform SBI

	CBO		**this note**		**ratio to CBO**	
	opt 4	opt 5	opt 4	opt 5	opt 4	opt 5
Nsbi	368	156	240	102	65%	65%
Mtot	468	82	295	70	63%	84%
M/N	1,272	532	1,229	686		

Columns four and five give the SBI number, mass on orbit, and mass from this note from Eq. (4) for 25-45 degree coverage with ranges from Eq. (1) for 5-minute burn liquid missiles, 10 and 20 g SBI accelerations, and 60 sec delay. The bottom row gives the average SBI masses. The 1,229 kg for option 4 is within 4% of the CBO's. The 686 kg mass for option 5 is higher by a ratio 576/442 = 30% due to the CBO's treatment of the thrust penalty at option 5's 6 km/s speed.

The final two columns give the ratios of the constellation sizes and masses from this analysis to those from the CBO Report. For option 4 this gives a SBI ratio lower by about a third than the CBO's, which is expected from the discrepancy between the ranges of Fig. 1 and those of CBO Fig. 2-2. Since this analysis reproduces the SBI mass for the low speed option 4, that implies the mass on orbit for option 4 should be below the CBO's by a like amount, as seen in the bottom row of column six.

The top row of column seven shows the ratio of constellation sizes for option 5, which is the same as for option 4, as it reflects the same fractional discrepancy in SBI ranges between Fig. 1 and CBO Fig. 2-2. Because this note's SBI masses are heavier by the thrust penalty than the CBO's for option 5, the on-orbit masses only differ 15%.

These discrepancies in SBI constellations and masses result directly from those in SBI range and booster models discussed above. The overall magnitude of the discrepancies is 15-30%, which is significant, but not large enough to impact the comparisons and conclusions below.

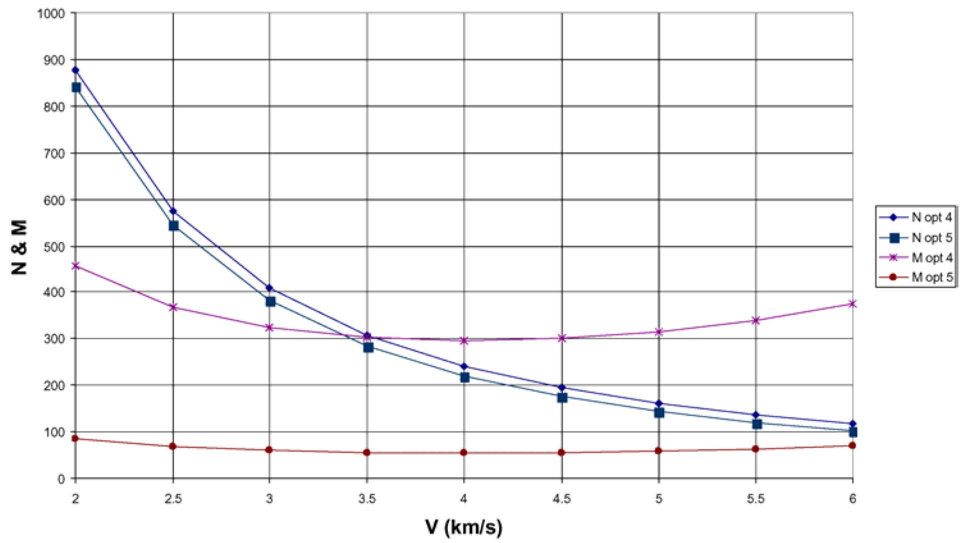
Summary. Constellation placement and sizing is as important to overall constellation mass as the SBI mass and distribution. The calculation of constellations size is straightforward and somewhat more defined than the latitude extent of the areas to be covered. The CBO does not give its analysis and the APS's is incomplete, but the differences between the three approaches appear small.

IV. Mass on Orbit

This section predicts the mass on orbit for uniform constellations and evaluates its variation with SBI speed and delay time, starting with speed, which has been discussed as a way to minimize constellation size. Increasing speed does reduce constellation size, but it the increase in mass per SBI with speed more than offsets that advantage. The optimal velocity can be understood from fundamental geometric reasons. These results are only moderately sensitive to SBI delay time.

Total mass on orbit is shown in Figure 5 as a function of SBI speed. At low V the two highest cures are the constellation sizes N for 60 s delay times. The mass curves M result from multiplying these N by the SBI masses of Fig. 3 and the constellation fraction f from Fig. 4 for 25-45 degree coverage. The V = 4 and 6 km/s values are for CBO options 4 and 5 in Table I. Both constellation sizes fall as $N \propto 1/R^2$ in accord with Eq. (9). The curves for option 4 and 5 differ by less than 10% throughout, so the difference in mass on orbit between them is not due to differences in their SBI acceleration or speed.

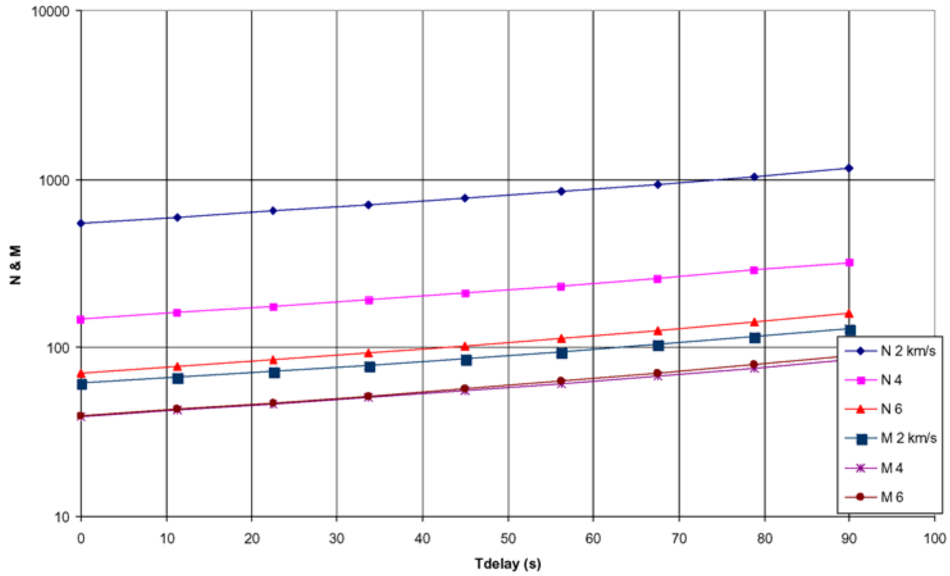
Fig. 5. Constellation size N and mass on orbit M vs SBI speed V



The differences in mass are primarily due to the 136/30 = 4.5-fold difference in assumed KV masses. Multiplying the mass for option 5 by 4.5 reproduces the option 4 mass curve. Both curves have minima at ≈ 4 km/s that are relatively flat and insensitive to SBI and missile parameters. The minimum in the curve for option 4 is ≈ 295 tonne at 4 km/s. It rises to 455 at 2 km/s and 375 tonne at 6 km/s. For a 30 kg payload and a single SBI per missile, these values agree with CBO Fig. 3-3 to the accuracy with which it can be read. This insensitivity of constellation size and mass to SBI speed indicates that V is not particularly useful for reducing mass on orbit for uniform SBI distributions.

Geometry. The velocity that minimizes constellation mass results from the distribution of SBI over a sphere. For fixed KV mass Eq. (6) SBI shows mass scales on velocity as $\propto e^{V/c}$. For uniform coverage the number of SBI scales as $\propto 1/R^2 \propto 1/(VT)^2$. Total mass on orbit is the product of the mass per SBI and the number of SBI, which for fixed burn time scales as $\propto (1/V)^2\, e^{V/c}$, which has a maximum at V ≈ 2c, seen in Fig. 4. Precise optimization can be performed analytically to study the variation of optimal V with T and SBI parameters. Lower velocities require larger constellations and greater mass. Higher velocities have fewer but heavier SBI, which would require multiple stages. The APS and CBO empirically find the optimum to be V ≈ 2c ≈ 4 km/s, confirming that higher velocities decrease the number of SBI but not the total mass on orbit.

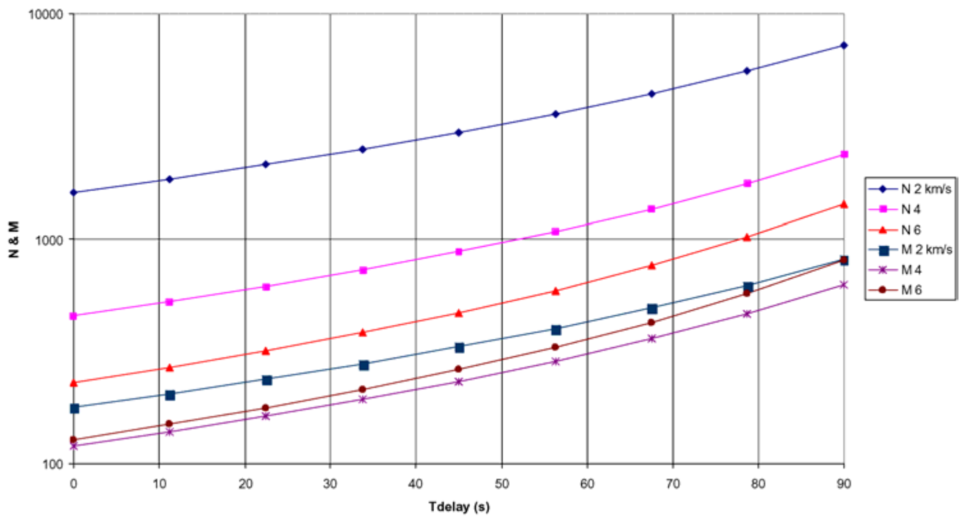
Fig. 6. Constellation size N and mass M vs Tdelay
liquid fuel missiles with 300 s burn time



Impact of delay time on constellation size and mass for liquid fuel missiles is shown in Figure 6. The top curve shows the constellation size N for 2 km/s, which varies from 552 SBI at T_{delay} = 0 to 1,160 at 90 s. Those values are about a third lower than CBO Fig. 3 for reasons discussed above. N increases exponentially with T_{delay} with exponent ≈ ln (1160/552)/90 s ≈ 0.0083/s, which also characterizes the curves for other speeds. The curve for 4 km/s is a factor of ≈ 3.7 below the one for 2 km/s'; that for 6 km/s is a factor of ≈ 7.8 below it for all T_{delay}. The bottom three curves are for mass M. The curve for 2 km/s SBI mass increases from 61 tonne at T_{delay} = 0 to 129 tonne at 90, which is about a third of that in CBO Fig. 3. The curves for 4 and 6 km/s are about a third lower than that for 2 km/s. The curves for 4 and 6 km/s are roughly equal throughout because the 4 km/s SBI's lighter KV just offsets its larger constellation size.

Figure 7 shows variation with delay time for solid fuel missiles. The top three curves for 2, 4, and 6 km/s scale exponentially as ≈ 0.014/s up to about 45 s, after which they increase more rapidly. That for 6 km/s increases more rapidly than the others for T_{delay} > 45 s, which is reflected in its mass. The 6 km/s SBI's mass is about equal to the 4 km/s SBI's at T_{delay} = 0, but approaches that of a 2 km/s SBI at T_{delay} = 90 s. There, both masses are ≈ 30% above that for a 4 km/s SBI, which agrees with the ratios of masses on orbit for 3-minute burn solid missiles shown in CBO Fig. 4.

Fig. 7. Constellation size N and mass M vs Tdelay
solid fuel missiles with 180 sec burn time



Summary. Total mass on orbit is the product of SBI mass and constellation size. Their product has a minimum at ≈ 4 km/s, relatively insensitive to SBI and missile parameters. The minimum is determined by fundamental geometric factors. It has some sensitivity to operational delays, but it is shown below that even that sensitivity is reduced for limited, restricted rogue constellations.

V. Cost

This section discusses the cost of SBI constellations. To do so, it derives a model for SBI and constellation costs based on fundamental relationships between SBI components, costs, and constellations. It uses costs from the CBO's database for large satellites, recent commercial IRIDIUM system, and earlier DOD costing of small SBI.

The CBO Report suggests that costs are not optimized at the same velocity. That result is based on two point designs with historical costs. The parameters in the CBO model can be used to support a wider variation of constellation cost with SBI velocity and cost parameters. Mass on orbit, M, is the product of the KV mass, K, the booster to KV mass stage ratio, S, the space craft to SBI mass lifejacket ratio, L, and the number of SBI in the constellation, N, which are related by

$$M = K\ S\ L\ N, \tag{10}$$

where N is computed from Eq. (9), S from the booster model of Eq. (6), and K and L are parameters defined in the CBO and APS reports and discussed above. These relationships imply the nested set of costs:

$$C = [C_K K + C_B K(S - 1) + C_J KS(L - 1) + C_L KSL]\ N, \tag{11}$$

where C is the total cost of the mass on orbit, and C_K, C_B, C_J, and C_L are the cost per unit mass of KVs, boosters, lifejackets, and launch services. K(S – 1) is the mass of the booster, net of the KV. KS is the mass of the SBI. KS(L – 1) is that of the lifejacket, and KSL is that of the spacecraft with its lifejacket. The masses in Eq. (11) are known from the calculations above, so the cost parameters can be inferred from the component costs in CBO Table A-4.

Table II. SBI component unit costs

CBO implied costs	Mass produced SBI costs
CB = $5.8 M/457 kg = $12.7M/tonne	same ($12.7M/tonne)
CK = $13.3M/30 kg = $443M/tonne	$56.5M/tonne
CJ = $6.6M/81.4 kg = $81M/tonne	same (CJ = CK/6)
CL= $10M/tonne → =$20M/tonne	$15M/tonne → $20M/tonne

The costs per unit mass are shown in Table II for the CBO's V = 6 km/s option 5, where KV and seeker masses and costs are lumped together because they are of a similar level of technology. The CBO survey gave launch costs of $11M/tonne, but it uses launch costs of C_L =$20M/tonne in its analysis, (p. 46), so that value is used for comparison below. The booster has the smallest cost per unit mass, but the greatest mass, so it makes a significant contribution to cost total. The CBO launch cost is 2-fold higher than its unit booster cost; its unit lifejacket cost is 2-fold greater than that of launch; and its kill vehicle is about 5-fold greater than its lifejacket. KV unit cost is the largest by an order of magnitude, so the range of plausible C_K is an important parameter. The CBO report cites unpublished reports that aggregate data from a number of large military satellites, which were built one at a time, essentially by hand.

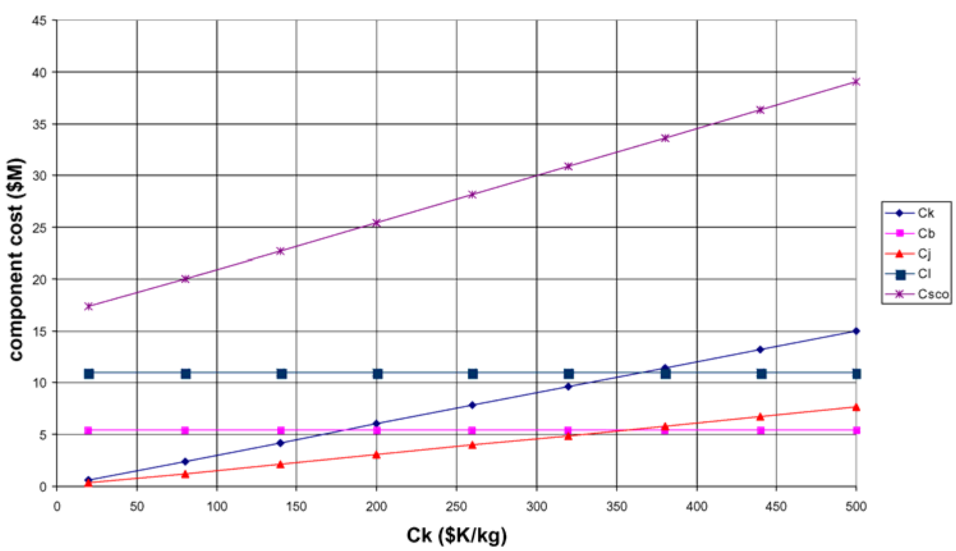
IRIDIUM is a more relevant, recent basis for the small, high volume SBI of interest here. It had an initial build of 72 satellites with 670 kg payloads comparable in complexity to SBI. They were produced on an assembly line at an average rate of one satellite per week and placed on orbit for a \$3.5B, including an average launch cost of \$10M/satellite ≈ \$14K/kg.[7] IRIDIUM does not compute the cost of individual satellites because production showed significant learning, which caused later satellites to cost a small fraction of the early ones. However, for comparison with the CBO this note divides the total cost by the mass on orbit and removes the actual launch costs to arrive at an effective IRIDIUM cost per unit mass

$$C_{KI} = \$3.5B/(72 \text{ x } 0.67 \text{ tonne}) - \$14M/\text{tonne } C\$71.5 - 15 \approx \$56.5M/\text{tonne}. \quad (12)$$

which indicates that payloads of complexity comparable to SBI KV can be mass-produced for unit costs an order of magnitude smaller than those inferred by the CBO from low-rate military programs. These inferred IRIDIUM parameters are used as surrogates for a mass-produced SBI constellation in the right column of Table II.

The bottom row indicates that actual IRIDIUM launch costs of \$15M/tonne are replaced by the CBO's \$20M/tonne for ease of comparison. The mass-produced lifejacket cost is assumed to have the same relationship to KV costs ($C_J \approx C_K/6$) as that in the CBO Report. Booster unit cost is taken to be the same. The KV cost is varied between the CBO value and the \$56.5M/tonne inferred from IRIDIUM in comparisons below.

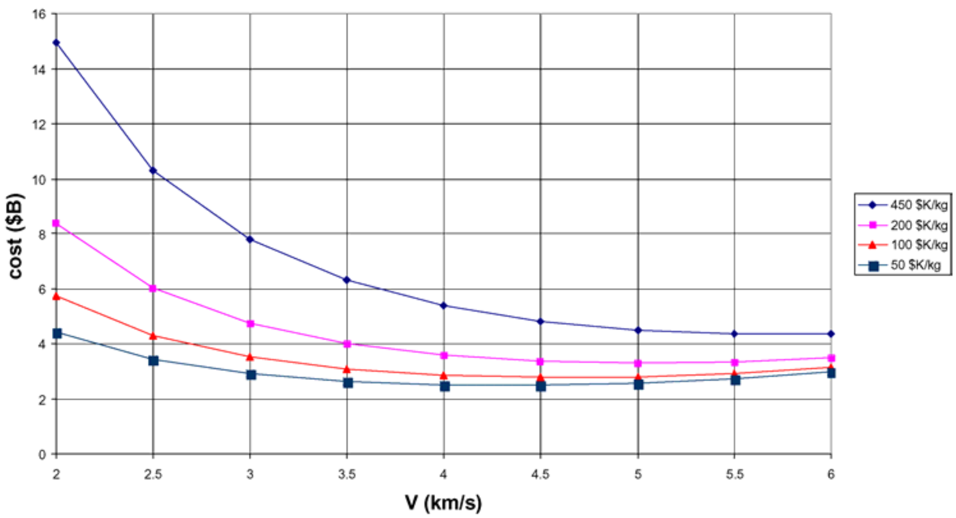
Fig. 8. Cost of SBI components vs kill vehicle KV cost/mass Ck



[7] R. Leopold, private communication, 8 September 2004.

Figure 8 shows the variation of SBI costs as KV unit cost C_K varies from \$20M to \$500M/tonne. KV cost is proportional to C_K, so it increases from \$0.6 to 15M as C_K varies from the IRIDIUM to CBO unit costs. Life-jacket cost remains in the same ≈ 50% ratio to KV cost as in CBO option 6. Booster cost does not change because V does not vary. Launch cost does not change because SBI mass does not vary. The total cost of an SBI on orbit varies from \$18 to 39M. At C_K = \$440M the KV is the dominant cost, and the SBI cost ≈ \$36M of CBO Table A-4. At the IRIDIUM cost of \$ 55M/tonne the KV is a minor contributor and the SBI cost drops to ≈ \$18M. There the major contributors are SBI booster and launch costs, which largely scale on SBI booster mass, in accord with the common approximation that mass on orbit is a good surrogate for constellation cost.

Fig. 9. Cost of mass on orbit vs SBI speed V
Liquid missile, 300 s burn time, 60 s delay



Constellation cost. Figure 9 shows the cost of total mass on orbit for the intercept of liquid missiles using SBI using KV unit cost parameters of C_K = \$50, 100, 200, and 450M/tonne in Eq. (6). For \$50M/tonne the cost curve resembles the mass curves of Fig. 5. It has a minimum ≈ \$2.5B at 4 km/s. It is fairly shallow, so there is little penalty for operation off optimum. For C_K = \$100M/tonne the minimum increases to ≈ \$2.8B at 4.5 km/s, but the cost curve is still shallow. For C_K = \$200M/tonne the minimum increases to ≈ \$3.3B at 5 km/s. The penalty for operating at larger V is small, but there is a ≈ 2.6-fold penalty for operating at V = 2 km/s. For C_K = \$450M/tonne the minimum increases to ≈ \$4.3B, and the penalty for operating at 2 km/s is a factor of 3.5.

Total costs are relatively insensitive to C_K below \$200M/tonne as long as the SBI operate at or above optimal velocities. Then costs only increase 30% as C_K varies from \$50 to 200M/tonne, an increase of 400%.

The costs in Figs. 8 and 9 are for liquid fueled missiles. Those for solid fueled missiles are similar but shifted up by a factor of ≈ 4.8. Total mass on orbit scales as $(1/VT)^2 e^{V/c}$. Solid missiles decrease T, but do not change the velocity that minimizes mass, which remains ≈ 2c independent of T. Thus, mass and cost vary as $1/T^2$. Solid missiles decrease T ≈ 2-fold, which produces a ≈ 4-fold increase in mass on orbit. Minima move to slightly lower V but remain relatively insensitive to C_K, so V = 4 km/s is near optimal for all but the highest unit costs. For kill vehicle unit costs of C_K = \$50, 100, 200, and 450M/tonne, the costs of mass on orbit for solid missiles are ≈ \$12, 13.7, 17.2, and 25.8B, which lead to the ≈ 5-fold increase for solids cited above.

Brilliant Pebble. For unit KV costs of C_K = \$50M/tonne and V= 4 km/s, the costs for SBI for liquid missiles are divided about equally between its booster, KV, lifejacket, and launch and total ≈ \$10M for the resulting 211 kg SBI. The Brilliant Pebble (BP) is the only SBI for which the DOD has executed a detailed bottom-up cost analysis. The design BP has a wet mass of ≈ 40 kg, a factor of ≈ 5 lower than the 211 kg design above. That scales on mass to a cost of ≈ \$2M, which is roughly the value associated with the CARD. Thus, the Brilliant Pebble cost scaling at low mass is consistent with that observed in IRIDIUM at intermediate mass and volume production and is connected through the variation of one parameter, KV unit cost, to the costs of large systems and low production rates studied by the CBO.

Summary. The APS Report does not estimate costs, but the CBO Report provides a summary of the database for large satellites. This note complements it with the mass and cost of IRIDIUM, a family of small, high volume satellites more directly relevant to SBI, and Brilliant Pebble, the one system in this class costed in detail by the DoD. It also derives a cost model that can be used to integrate these costs and to consider the variation of constellation costs with component cost—particularly for KVs. For IRIDIUM cost levels, total cost curves resemble constellation mass curves, in part because the dominant components are booster and launch costs. At CBO cost levels KV the optimal speeds are less sensitive to SBI and missile parameters and increase slowly with KV costs.

VI. Life cycle cost

Life cycle costs are constructed by augmenting the constellation costs derived above with fixed costs R&D, operations, test, and integration. The APS does not treat those fixed costs, but the CBO does provide parametric estimates for them. For liquid missiles the fixed costs are estimated to be about two thirds of the total. For solids they are about a third. The largest of the fixed cost is R&D, which is largely allocated.

Life cycle costs use the costs for the initial constellations from the previous section and add the variable costs for interceptor replacement and launch and the fixed costs for R&D, operations, test, and integration. The CBO report estimates variable costs based on SBI lifetimes of ≈ 7 years (2 replacements over 20 years) and fixed costs scaled from large space systems. For V = 4 km/s, SBI deployment cost from Fig. 9 of $2.5B for liquids and $12B for solid missiles gives life cycle costs shown in Table III. For liquid missiles the $2.5B cost for the initial constellation is that shown in Fig. 9. The $5B below it is the cost of replacing the constellation twice. The R&D is an allocated fraction of the budget for large space systems. The $3.6B for operations, test, and integration are estimates for the cost of an operating system that has not been designed yet. The $12B for solid missiles is that discussed above. The $24B is for replacements. The other costs are assumed to be essentially the same as for liquids.

Table III. Life cycle costs, uniform SBI constellations, liquid & solid missiles

	Liquid	Solid
Initial constellation	2.5	12
Replace constellation	5	24
R&D	8.5	8.5
Ops	1	1
Test	1.6	1.6
Integration	1	1
Total life cycle	$19.6	$48.1B

The $19.6B life cycle cost for a SBI constellation for liquid missiles is modest compared to offensive strategic systems, the midcourse missile defense system it is to complement, and the CBO cost estimate for a surface-based interceptor that can at most intercept missiles from North Korea. It is well below that of the 10 km/s surface-based interceptor needed to address missiles in boost elsewhere. It is not appropriate to compare the $48.1B for a SBI defense against solid missiles with that of surface-based systems, as APS and CBO analysis indicate SBI can engage solid missiles successfully, while low velocity surface-based systems generally cannot from secure bases.

The CBO cites life cycle cost of $27 to 56B for SBI constellations for liquid missiles. The differences between its $27B and $20B estimates in Table III are due to the differing assumptions about KV unit costs discussed above. CBO uses historical costs for large satellites. Figure 8 shows that roughly doubles KV mass and SBI cost and increases life cycle cost by $7.5B to $27.1B, which is close to the CBO value of $27B.

The range of $27 to 56B in CBO estimates results from the 4.5-fold difference in mass between the KVs for options 4 and 5. That increases SBI costs in Table III by factors of 4.5 to 4.5 x $7.5B = $33.75B for a total of $33.75B + 12.1B = $45.85. That accounts for 75% of the maximum value estimated by the CBO.

The CBO estimates an incremental cost of $30-40B to address solid missiles, but it does not present a detailed estimate of the costs of the SBI needed. The calculations above indicate an increment of ≈ $48.1 – 19.6B = $28.5B, which is used to add more SBI whose performance is similar to that needed for liquid missiles.

Fixed costs. For liquid missiles two thirds of the costs in Table III are fixed. SBI sensors have successfully remapped the Moon, their engines have been flight tested, and its KV has been brassboarded and tested in the laboratory, so it is unclear why R&D should be half the SBI life cycle cost. SBI command, control, and communication are either carried on the SB themselves or available from the MDA network (CBO p. 52), so it is not clear that extensive integration is needed. And the constellation's main elements remain dormant until released, it is not clear why $2.6B is needed for the operation and test. These allocated costs were argued and ultimately avoided in Brilliant Pebbles.

CBO suggests GPS should be used as a model for SBI operations and costs, but it is not an appropriate comparison. IRIDIUM operates constellations of comparable complexity to GPS and military satellites with crews that are 100-fold smaller. Direct broadcast TV operates them with 100-fold smaller crews. Thus, conventional military operations such as GPS do not appear to be an appropriate model for the operation of SBI constellations, which could be operated with smaller and cheaper work forces.

Commercial operations also provide useful data on component lifetime. IRIDIUM launched a total of 95 satellites, of which only 16 have been decommissioned. Thus, its 66 satellite operational constellation will remain operational with no additional satellites until 2014, which is a ≈ 20 year life time rather than the 7 year lifetime assumed in CBO life cycle estimates. Military and commercial satellites also tend to have useful lifetimes much longer than their design lifetimes.

An important fixed cost in cross-comparisons between surface- and space-based interceptors that is omitted in the CBO analysis is the cost of sensor and communications assets needed to support surface-based systems. MDA experience with the Initial Defense against threats from North Asia indicates the cost of such support systems can be large, because they require reliable, wide-area coverage. Surface-based systems require dozens of navy ships whose capital and manpower costs could greatly exceed those of the SBI constellations discussed above.

Exchange ratios. Variable costs of $7.5B ($ 2.5 initial SBI + $5B replacement) are spread over 3 constellations of 240 SBI each for an average cost of ≈ $100M/SBI, so if a SBI has kill probability p = 0.9 and missiles (or their targets) have value of ≈ $1B, the first SBI committed to a missile has a favorable exchange ratio 0.9 x $1B : $100M/SBI = 9:1. A second SBI faces a target with expected value (1 – p)$1B; which produces an exchange ratio ≈ 0.9 x $0.1B : $100M/SBI, which is ≈ unity. Thus, committing two SBI per missile a suggested above is economically sound, although economic considerations are not dominant for rogue ICBMs. Simultaneously committing two SBI is feasible. Contrary to CBO's statement (p. 43), there is not enough time to exercise shoot-lookshoot in boost phase engagements.

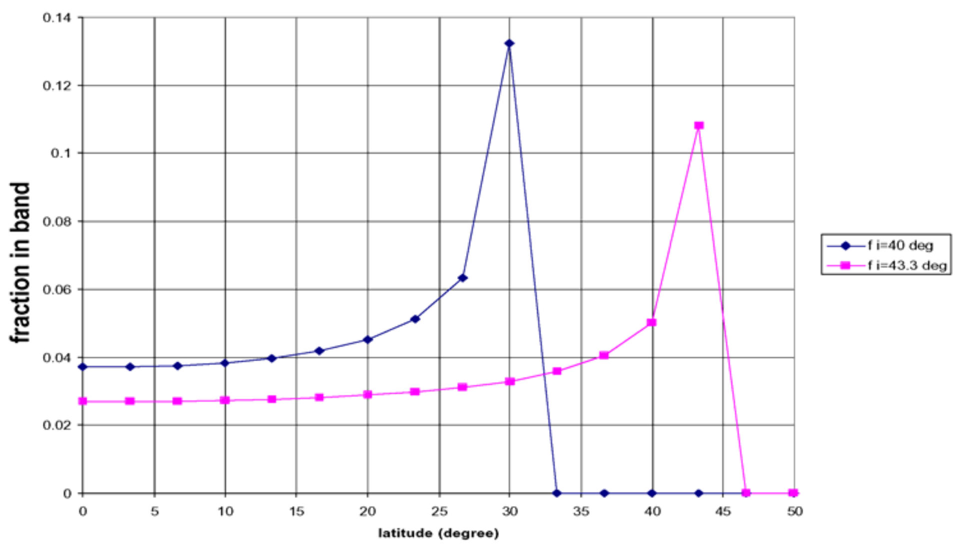
Summary. Life cycle costs add the constellation costs from the previous section to the fixed R&D, operations, test, and integration costs discussed above. The APS does not treat costs. The CBO provides parametric estimates of costs for military systems. This section adds costs for commercial high volume systems and DoD small SBI. For liquid missiles the fixed costs are estimated to be about two thirds of the total. For solids they are about a third. The largest of the fixed cost is R&D, which is largely allocated. The estimate of life cycle costs is about $20B for liquid missiles and $50B for solids. For the former, about 2/3 is for fixed costs. For the latter, about 1/3 is for fixed costs. Given the state of development of the component technologies, the size of the fixed costs estimated seems excessive relative to those for variable SBI costs.

VII. Concentrated Coverage

Previous sections discuss constellations that uniformly cover large bands of latitude. This section departs from that to discuss concentrated coverage of threats that are limited in latitude. Concentration is accomplished by inclining the SBI constellation at the latitude of the threat, which enhances coverage there an order of magnitude. That supports early coverage of such threats with a modest number of SBI, increases the frequency of SBI revisits, and reduces their sensitivity to operational delays.

Coverage. The CBO and APS Reports assume it is necessary to deploy SBI over much of the Earth's surface for them to be effective. Such broad coverage is ultimately desirable, but not required for current rogue threats, which are confined to narrow bands of latitude such as North Korea. Deploying SBI only over the latitudes of those threats reduces the number of SBI required, making it possible to achieve continuous coverage of rogue threats earlier.

Fig. 10. Fraction of satellites in latitude band vs latitude 3.4 degree bands



Inclining SBI at the latitude of the threat produces a peak concentration there an order of magnitude greater that that from a uniform distribution of SBI.[8] Figure 10 shows the fraction of SBI from constellations in-

[8] R. Garwin, "How Many Orbiting Lasers for Boost-Phase Intercept?" *Nature*, 315, 23 May 1985, p. 286.

clined at 43 and 30 degrees in 3.3-degree bands, which are roughly the width needed to cover trajectories of missiles from North Korea. For the former a fraction f ≈ 11% of the SBI are in the northernmost band over the threat; for the latter ≈ 13% is in the band. The fraction falls at lower latitudes, so little coverage is wasted at low latitudes where there are currently no threats.[9]

At their northmost latitude all SBI are headed due east, which produces a ring of eastward moving SBI on a line of latitude λ equal to the constellation inclination. The circumference of the ring is $2\pi R_e \cos\lambda$, so SBI with range r need $2\pi R_e \cos\lambda/2r$ SBI to cover the circle. If the fraction of SBI in the northmost band is f, the constellation size needed for complete, single coverage is

$$N_I = \pi R_e \cos\lambda/rf, \tag{13}$$

for the minimum number of SBI needed to assure no gaps in coverage. The time between passage of successive satellites is $r/V = \pi R_e \cos\lambda/fN_I V \approx 1$ minute for 300 SBI. Unless missiles could be launched at shorter intervals they could be addressed by successive SBI without increasing constellation size.

Constellation size. Figure 11 compares the size of uniform, N_U, and concentrated, N_I, constellations as functions of SBI velocity. At low V the two top curves are for APS uniform coverage to 45-degree latitude. The top curve is for solid missiles with 180 s burn times; the second for liquid missiles with T = 300. Both would require thousands of satellites at V = 1-2 km, but their constellations drop to ≈ 1,440 and 320 SBI respectively at 4 km/s, in approximate agreement with the APS Report.

The two bottom curves are for concentrated coverage to 45-degree latitude of 180 s solid and 300 s liquid missiles. They require 590 and 280 SBI at 2 km/s where their mass optimizes. Thus, uniform and concentrated coverage require roughly equal numbers of SBI for liquid missiles, but uniform coverage requires about twice as many SBI for solid missiles. That is because concentrated coverage scales on missile burn time as 1/T, while uniform coverage scales as $1/T^2$. The ratio of uniform to concentrated coverage scales as 1/T which is a significant penalty for solid missiles.

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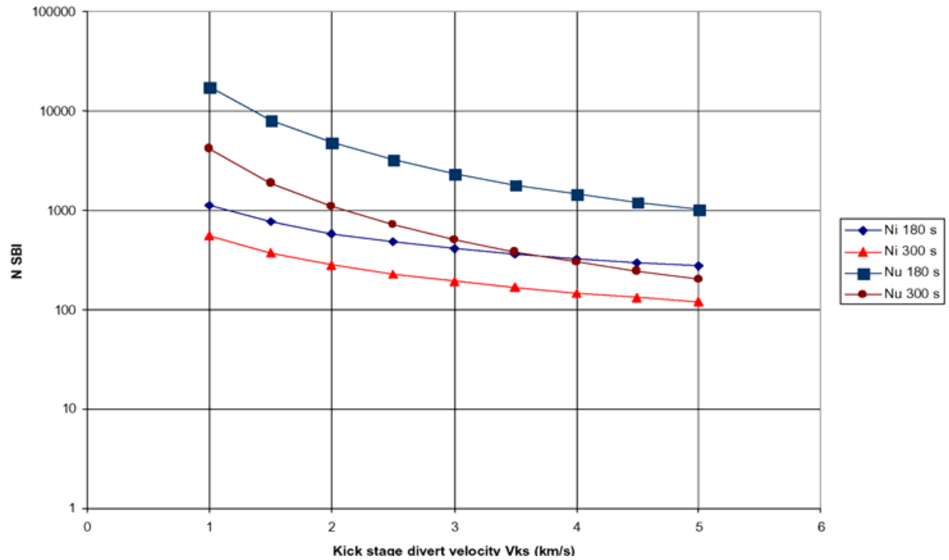
[9] G. Canavan, "Concentration of Space-Based Interceptor Constellations," Los Alamos LA-UR-02-5739.

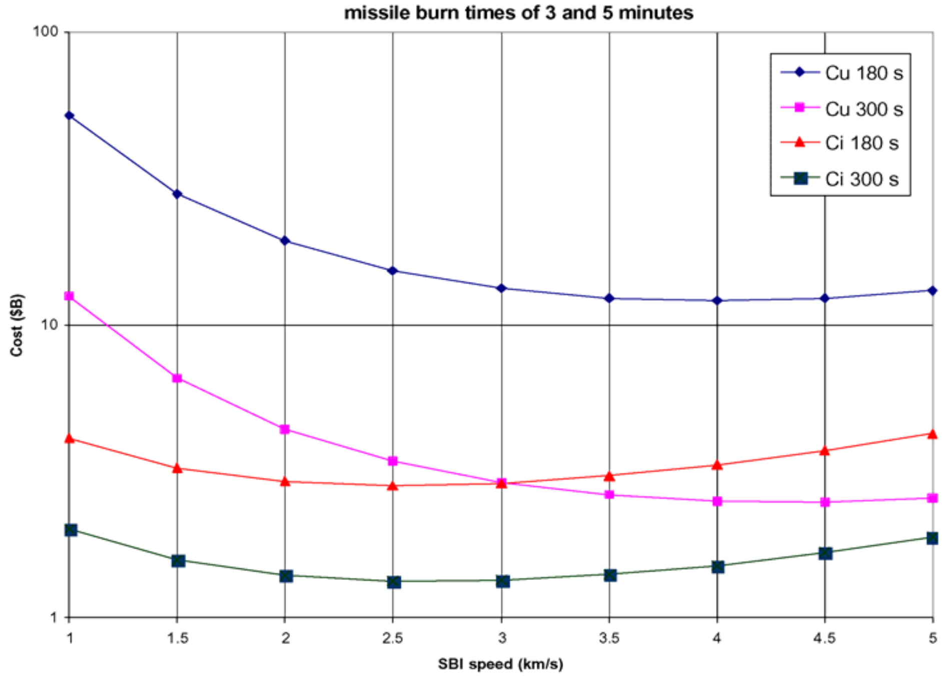
Fig. 11. Constellations for single inclination & uniform coverage, Ni & Nu



In addition to this reduction in SBI number by concentration, Fig. 3 shows that the mass of the SBIs needed for concentrated coverage is lower by a factor of ≈ 2.4 due to their 2-fold lower speed. Shifting the optimal velocity to a lower value also means the SBIs for concentrated coverage can use simpler, single-stage boosters, which should make the production of low-mass SBI cheaper and less demanding. Reducing sensitivity to missile burn time by concentration also has the derivative effect of reducing the sensitivity of the constellation to operational delays in SBI command and control.

Mass on orbit. Figure 12 compares the total mass on orbit for uniform, M_U, and concentrated, M_I, constellations as functions of SBI velocity for coverage to 45 degrees. At low V the two top curves are the mass M_U for uniform APS with 140 kg KVs. The top curve is for solid missiles with 180 s burn times; the second for liquid missiles with T = 300. Both have minima at V ≈ 4 km/s. Uniform constellations total mass $M_U \propto (1/r)^2 e^{v/c}$, which has a minimum at V ≈ 2c. The liquid missile curve has minimum ≈ 360 tonnes. The solid curve has a minimum of ≈ 1,800 tonnes, which is a factor 5 higher than the liquid, in accord with the scaling that for fixed V, MU $\propto (1/T)^2$.

Fig. 13. Cost of uniform and single inclination SBI constellations vs SBI speed missile burn times of 3 and 5 minutes



The two bottom curves are for concentrated coverage over the latitude of North Korean by SBI with the 30 kg option 5 CBO KV. The number of SBI needed to cover the circle at the northmost latitude of concentrated constellations scales as $N_I \propto 1/r \propto 1/VT$, so the total mass on orbit scales as $M_I \propto e^{v/c}/(VT)$ whose minimum is at $V \approx c \approx 2$ km/s. The third curve for T = 180 s solid missiles has a minimum ≈ 65 tonnes; the bottom curve for 300 s liquids has a minimum of ≈ 31 tonne.

Shifting from uniform to concentrated coverage and 30 kg KV mass reduces the total mass on orbit for uniform coverage of liquid missiles from ≈ 355 tonne on the second curve at 4 km/s to ≈ 31 tonne on the bottom curve at 2 km/s. Of this 11.5-fold reduction, a factor of 4.5 is due to reducing the KV mass from 140 kg in the top two curves to 30 kg in the bottom two. The remaining factor of 11.5/4.5 ≈ 2.5 is due to concentration. As the minimum is fairly shallow, these masses would only be increased ≈ 25% by operation at up to ≈ 4 km/s.

The reduction by concentration is larger for solid missiles. The overall reduction from the top to the third curve is a factor of ≈ 1,720/65 ≈ 26.5, of which ≈ 4.5 is again due to the CBO KV and ≈ 26.5/4.5 ≈ 6 is due to concentration. This large reduction in the largely eliminates the impact of solid missiles. For uniform coverage, $M_U \propto 1/T^2$, so halving the missile burn time in going from liquids to solids would increase constellation size by a factor of ≈ 4, as seen in Fig. 11. For concentrated coverage, $M_I \propto 1/T$ so halving the burn time would only increase constellation size a factor of 2. Under that scaling solid missiles are within a factor of two of liquid missiles throughout.

The APS did not challenge the technical feasibility of SBI, but it expressed concern, based on the strong sensitivity of uniform constellation size and mass to missile burn time, that constellations could be of unacceptable sizes for solid missiles. That is not the case with concentrated constellations, whose sizes vary only slightly with threat burn time. The APS's stated reservations do not apply to concentrated constellations.

Costs. Mass reductions by concentration imply cost reductions through Eqns. (5) and (6). Figure 13 shows costs as functions of SBI speed for liquid and solid missiles using the costs for mass-produced SBI from Table II. At low V, the top curve is for uniform coverage of 3-minute burn solid missiles, which has a minimum of ≈ \$12B at ≈ 4 km/s. The second curve is for uniform coverage of 5-minute liquid missiles, which has a minimum ≈ \$2.5B at slightly above 4 km/s. The third is for concentrated coverage of solid missiles, which has a minimum of ≈ \$2.8B at 2.5 km/s. The fourth is concentrated coverage of liquid missiles, which has a minimum of ≈ \$1.3B at ≈ 2.5 km/s.

The separations in cost are not as great as Fig. 12's separation in mass, but the trends are clear. For liquid missiles, the ≈ \$1.3B cost of concentrated coverage at 2.5 km/s is a factor of ≈ 2 less than that for uniform coverage at 4.5 km/s. For solid missiles, the cost for concentrated coverage at 2.5 km/s is a factor of ≈ 4.3 lower than the \$12B for uniform coverage at 4 km/s.

For concentrated coverage the constellation cost is ≈ \$1.3B for liquid missiles and \$2.8B for solids. The former is about a factor of 2 lower than the \$2.5B of the CBO Report for the same KV costs. The latter is about a factor of 12/2.8 = 4.3 lower, largely due to the favorable scaling of concentrated coverage.

Using these costs for concentrated coverage and the CBO's three constellation (initial plus two replacements) prescription gives on orbit lifetime costs of $3.9B for liquids and $8.4B for solids. With CBO fixed costs, that gives life cycle costs of $16B and $20.5B. Although SBI costs are reduced by factors of 2-4 from the CBO Report, life cycle costs are only reduced by 25% due to the large fixed R&D and operating costs assumed in the CBO Report. These low SBI costs do mean that defensive constellations are relatively insensitive to changes in the size and technical attributes of the threat as well as to the detailed performance of the SBI.

The fixed R&D, integration, operations, and test costs inferred from historical data do not appear appropriate for mass produced systems. As noted above, the total cost of mass on orbit for the IRIDIUM was under $3.5B. Its total cost, including dedicated R&D integration, operations, and test, was said to be $5-6B, which gives an overhead of ≈ $1.5B/$3.5B ≈ 4% rather than the CBO's ≈ 200%. With that ratio the life cycle costs become ≈ $3.9 x 1.4 ≈ $5.5 for liquids and $8.4B x 1.4 ≈ $12B for solid missiles. As noted above it is not clear that operation and test should be a significant expense for SBI that are to be inert until released, but the history of the Brilliant Pebble program does indicate that operators tend to insist on larger roles, which would increase costs.

Summary. This section treats concentrated coverage of threats that are limited in latitude by inclining the SBI over the threat, which enhances coverage there. That supports early coverage with a modest number of SBI, increases the frequency of SBI revisits, and reduces their sensitivity to operational delays. The decreases in constellation size are on the order of 2-4. The decreases in mass can be several orders of magnitude. The decrease in cost is a factor of ≈ 6 for solids, but the accompanying reduction in sensitivity to burn time largely eliminates the impact of solids on SBI.

VIII. Broader Coverage

This section discusses the constellations for coverage of threats that have greater latitudinal extent and indicates how they emerge as the limit of successive concentrated constellations.

Broader coverage. The CBO report assumes that coverage of Iran and N. Korea requires a uniform constellation from 25 to 45 degrees latitude. North Korea covers only a few degrees. Iran extends from 25 to 40 degrees in latitude, but it is not necessary to cover the whole country if missiles are in initially based in fixed launch sites, as is typically the case. If missiles are placed in a single site or a set of sites spread over a few degrees in latitude, coverage can be produced by a band of SBI inclined over that latitude. A deployment there and another over North Korea could be accomplished with a constellation about twice the size of that for North Korea alone. Such constellations would still be an order of magnitude smaller than the uniform constellations assumed by the APS and CBO.

The CBO argues that missiles could be placed on mobile launchers and moved throughout the country (p. xvi), but that is not easy. SCUDs are so mounted, but ICBMs are much larger, so mobile basing is an unlikely first step. Russia accomplished mobile basing, largely along its trans-Siberian railway and road transport to pre-surveyed launch sites. China is attempting to develop mobile ICBMs. Thus, mobile missiles seem an unlikely reason to choose a uniform SBI constellation for an initial SBI deployment.

Missile submarines appear to be more pressing. North Korea is one of a number of countries purchasing diesel submarines capable of launching missiles that could reach the U.S. They are inferior to nuclear submarines as a secure retaliatory force because they can only remain submerged for a few days. However, they are superior as a first strike weapon because they are quieter when submerged.

The CBO report states “Proponents of space-based interceptors argue that the identity of future threats is uncertain and that coverage of the ocean is a valuable hedge against ICBMs launched from ships or submarines” (p. 34). That is correct; however, the Report does not note that SBI could cover submarines without adding to constellation size as submarines are covered by SBI that are away from land targets. Neither does the CBO note that the ground-based boost-phase concepts it discusses have no capability against submarine threats at all.

The CBO notes that “In principle a space-based system is also capable of covering very large countries—such as China or Russia—that are too big to be covered by surface interceptors located around their borders.” It then states “However, the constellations in Options 4 and 5 would not cover high enough latitudes to defend against missiles launched from those countries.” (CBO, p. 34)

Figure 14 shows the fraction of a full constellation needed for uniform coverage of China and Russia. The bottom curve for China extends from ≈ 21.5 to 53.5 degrees, a ≈ 5 degree extensions north and south to the constellation for Iran and North Korea. That increases the constellation fraction from ≈ 0.57 to 0.72 or 26%. The top curve is for Russia, which extends from ≈ 50 to 65 degrees. For that Fig. 12 gives f ≈ 0.5, so a constellation ≈ 12% smaller than that for Iran and North Korea would cover Russia, which has larger longitudinal extent but a smaller effective latitudinal extent. SBI are stressed by the former but insensitive to the latter. Covering all of Iran, North Korea, China, and Russia would require a fraction f ≈ 0.83, which would be a 46%. increase over that for Iran and North Korea.

The need to cover large areas without for local ground bases is of growing concern (CBO, p. xix). Artillery with ranges needed to attack ground bases near borders is now widely disseminated (CBO, p. 35), but few countries have the ability to attack satellites at altitudes of hundreds or thousands of kilometers on orbits that can be varied. China or Russia could possibly attack such satellites, but have little incentive to do so, as a SBI constellation sized for a single missile would have negligible impact on their strategic missile forces. SBI would instead provide insurance against accidental or unauthorized launches, which surface-based interceptors cannot do.

Fig. 14.Fraction of full constellation for uniform coverage for China & Russia

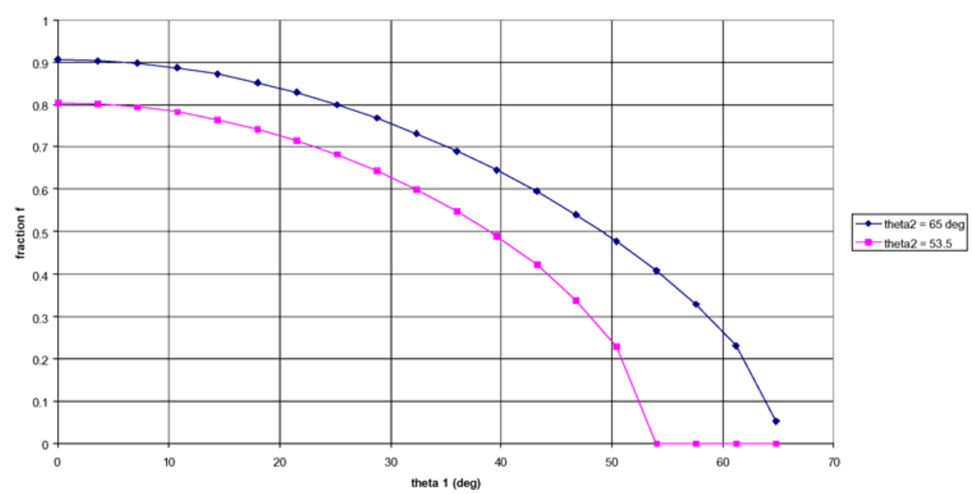


Fig. 14 and the sections above discuss uniform basing because it is the limiting deployment if and when threats require global defenses. As noted above, such defenses are best approached in steps, as needed, with successive increments to the constellation devoted to areas of emerging concern. As such areas are covered, the constellation with approach uniform coverage in an optimal manner. Global coverage would only require constellations about 1/0.57 ≈ 75% larger than the uniform constellations discussed above, which would not stress manufacturing or launch capacity. They would gradually require more SBI on orbit, but successive increments could take advantage of the best technology available at that time.

Summary. Constellations of large extent in latitude can be built by integrating the contributions of concentrated constellations over smaller threat areas as they emerge. The CBO and APS Reports assume that coverage of Iran and North Korea requires a uniform constellation from 25 to 45 degrees latitude, but North Korea covers only a few degrees and Iran is likely to use a fixed launch area for some time. Thus, a constellation inclined over each could cover all near-term threats with a constellation not much larger than that for North Korea. As additional threats emerge, SBI would be inclined over them. The limit is a constellation as close to uniform as required. Such constellations would also provide coverage of submarine threats at each level of deployment.

IX. Summary

This note derives analytic models for SBI range, mass, coverage, and constellation size; compares them to the models used in and results of the APS and CBO Reports; and extends them to concentrated coverage of small threats, which is not addressed by the earlier reports. Comparisons of kinematic parameters agree with the APS Report to within a few percent and with the CBO Report to within 25-50%, which is significant but does not prevent comparisons. This note and the APS KV and SBI mass agree to within a few percent. CBO SBI masses are ≈ 30% low, apparently due to its treatment of their thrust penalty at high speed. The three reports' estimates of constellation sizes are adequate for comparisons.

This note and the APS agree closely on the size of uniform constellations, total mass on orbit, and variation with SBI speed for the conditions of that report. CBO range and masses produce 50% larger constellations and 30% larger masses; however, the reasons for that are clear and can readily be traced through comparisons. For fundamental reasons all three reports produce optimal SBI speeds ≈ 4 km/s, constellation sizes ≈ 220 SBI, and total masses ≈ 50 tonnes for CBO 30 kg KV. These optima are determined by fundamental geometric factors. They are not strongly dependent on SBI performance or delay time, which is the key parameter characterizing defense responsiveness.

The APS Report does not treat costs other than those for launch. The CBO Report provides a survey of historical costs for military space systems. This report provides a complementary database for high volume production based on the recent IRIDIUM system and a framework for incorporating those data with the limited DoD costing of space based systems in this mass class.

For uniform constellations and CBO cost data, KV costs dominate. For IRIDIUM costs, launch and booster costs dominate. IRIDIUM costs produce optimal mass on orbit ≈ $2.5B for 4 km/s SBI. As KV costs rise towards the CBO's, total cost increases to ≈ $3B and the optimal speed to ≈ 5 km/s. Adding these on orbit costs to CBO's fixed cost estimates produces life cycle costs of ≈ $20B for liquid missiles and $48B for solid missiles, which are comparable to other strategic systems and to other elements of the current missile defense system.

While kinematic and component cost issues are important, there is more leverage in the choice of SBI constellations. Inclining constellations over the latitude of the threat can increase coverage there an order of magnitude, placing 10-15% of the constellation over the threat. That reduces the number of SBI needed for coverage, decreases the interval between successive SBI passages, and reduces their sensitivity to delay times. Concentrated coverage is the optimal way to sequentially deploy additional SBI as they become available, and it leads optimally to whatever end state proves necessary.

Such coverage reduces the number of SBI needed for initial coverage by a factor of 2 to 5 and the mass on orbit by a like amount. The APS Report expressed concern that uniform coverage could take 2,000 tonnes and stress U.S. lift capacity. Concentrated coverage would take ≈ 30 tonnes for liquid missiles and 30 kg KVs. That mass is two orders of magnitude less. It could be accommodated on a single heavy booster. Concentration also reduces optimal speeds to ≈ 2 km/s, which reduces the size of SBI and simplifies their design.

These reductions in mass on orbit imply similar reductions in the cost. Uniform coverage of solid missiles would cost ≈ $12B, but concentrated coverage of liquid missiles would only cost ≈ $1.3B. This order of magnitude reduction is important, but the reduction of the impact of fast burn missiles to a factor of two is even more important. It removes the APS's primary concern about SBI. Replacement constellations and fixed costs increase life cycle costs, but not to the level of competing systems, particularly when appropriate R&D, integration, operations, and test costs are used.

Concentration is the appropriate way to get coverage where it is needed as soon as possible with a limited number of SBI. It makes initial coverage possible at roughly a tenth the cost and size of uniform coverage. It is the optimal path to that end as well as to any ultimate end state. Global defense is possible with constellations slightly larger than those derived above.

X. Conclusions

Sections I-III show that this report and the APS's agree closely on SBI range, mass, and constellation size. The CBO report disagrees by amounts that are significant but do not prevent comparisons. The analytic models derived here are thus adequate for comparisons. That agreement extends to mass and cost of components on orbit, for which earlier space systems, IRIDIUM, and DoD small SBI systems provide useful and consistent normalization. Life cycle costs are linearly related to those of orbital components, so they also agree for a common set of fixed costs, although the fixed costs used by the CBO do not appear appropriate for mass produced SBI.

The largest area of disagreement is constellation concentration, which the APS and CBO Reports do not treat at all. Instead, they assume it is necessary to cover most of the globe for the SBI system to be effective against a single rogue country. In a boost phase defense only the SBI directly over the launch area can participate. Thus, if the goal is to defend against rogues at the earliest date possible with the smallest number of SBI, the optimal approach is to concentrate the SBI orbit over the latitude of that rogue. Thus, concentration is the appropriate way to begin coverage of a single rogue, the optimal way to expand the coverage to additional threats as they emerge, and the best way to approach whatever fraction of global coverage ultimately proves necessary.

Concentration is the key to eliminating the impact of solid missiles and reducing the impact of SBI delays. The analysis above indicates that it is more important than the details of SBI mass or cost models. The APS Report only treated uniform constellations, so its mass estimates are orders of magnitude larger than those needed for rogue threats. The sensitivity to solid missile burn time the APS cites as SBIs' primary weakness is removed by concentration.

The CBO Report also treated only uniform constellations; thus, its mass and cost estimates are an order of magnitude larger than those needed for rogues. The sensitivity of its masses and costs to solid missile burn times is also reduced to a factor of two by concentration. Thus, it is not that the APS and CBO Reports are incorrect, it is only that they address a different problem. Rather than treating today's problem of achieving defenses against one or two geographically concentrated rogues, they address the long-term problem of global space-based missile defense. However, they do so using today's technology and costs because they ignore the advantages in technology that will naturally accrue to progressive deployments as any additional threats emerge.

At present SBI's primary weakness is its immature KV and engine technology. These weaknesses could be removed and the apparent advantages of SBI thoroughly tested with modest investment. That could protect the SBI timelines needed to assure that they would be available when effective countermeasures to midcourse systems become available.

XI. Questions and Answers.

Question: How much impact does the trajectory of the missiles have on the cost line, do you think? In other words, you spent most of your time here looking at liquid boosters, No Dong and upgrades. What happens when flight times get shorter and you get more into the theater realm?

Canavan: I am sorry if it sounded that way. I did not restrict myself to liquids. I tried to give equal treatment to solid ICBM's, mostly because that is what most people have been worried about—excessively so, I think. Let me summarize their impact. For ICBMs, dropping from a five-minute burn time, the nominal burn time of liquid fuelled missiles, to three minutes, which is possible with a fast-burn solid missile, the impact on a uniform constellation of SBIs is to increase the constellation size by about a factor of four. That is the factor of four the American Physical Society argued could push SBI over the edge. For concentrated coverage of areas such as North Korea, it only costs the SBI a factor of two. As solid-state missiles are more expensive than liquid missiles, the shift to solid missiles might be favorable to the concentrated constellation and hence to the defense. As to your earlier question on how the analysis changes for theater missiles, I did that analysis for the Defense Science Board two or three years ago, so I may or may not remember it just right. It is hard to get theater missiles them in boost, which is what I am talking about here, because the duration of their boost phase is only a minute or so and they burn out at a few hundred km. Only for missiles ranges of 1500-2000 km can you intercept in boost affordably. On the other hand, short-range theater missiles do not get up that far out of the atmosphere, so they cannot use decoys all that effectively. Thus, for theater missiles, one can make a better case that ascent-phase or mid-course intercepts are useful. That is what I remember; I could dig up the reports if you are interested.

Question: You carefully avoided assessing the performance or comparing the performance of a system like this to the systems that will be coming on line in a year or two. Would you care to make a comment about that comparison?

Canavan: I think I made the relevant comments. This system is not a competitor for the mid-course defense that is going to come on-line in the next month. It is complementary. The system that is coming on-line soon is the one we know how to build. It is arguably the right system if we are faced with one or two North Korean or northeast Asian missiles with essentially no counter-measures on them. The problem of course, is that last phrase, countermeasures. The countermeasures required to stress that system have been discussed and tested for some time by some people who have shown very little restraint about selling that sort of technology to others. So, at some point, you would expect to see that countermeasure technology diffuse into northeast Asian missiles. Thus, I think it is important to have something like [the boost phase systems discussed here], so when those countermeasures show up and could degrade the effectiveness of the near-term system, we have something to complement it, extend, and maintain its effectiveness. So I don't regard them as alternatives; I think they fit together pretty nicely.

Question: On the countermeasure question, in watching the films of missile tests, the launches of the targets will actually spin out to burn fuel off because they have more fuel than they need. Isn't that a countermeasure that could be used as the rocket goes up to make it harder to intercept?

Canavan: You anticipate an issue that must ultimately be faced—particularly for solid missiles. With the liquid North Korean missiles, there is no need to do a maneuver like that and in fact it is pretty difficult to do, as they are not engineered to take those sorts of transverse g's. So I would not expect to see violent transverse maneuvers in the boost phase in the near-term.

When North Korea or other countries bring along solid missiles, they will, like us and Russia, have to GEMs maneuvers, which are out-of-plane maneuvers used to burn off excess fuel. Since solid rockets cannot be throttled back, you have to do such maneuvers with solid missiles just to get it down to an amount of residual fuel where you can truncate thrust reliably. Thus, in time we will see such maneuvers, and they will be just as much trouble as they were when we first ran into them back during SDI. We were surprised to learn that the Russians were doing such maneuvers. Then we were embarrassed to remember that our solid missiles were doing them too. But that is just how you get rid of excess energy. It is a complication, but it is one for which you have to be prepared.

Jeff Kueter: Please join me in thanking Dr. Canavan for his presentation today, and I thank you all for coming.

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